# Plant Breeding Strategies for Abiotic Stress Tolerance in Cereals

# 8

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## Abstract

By the year 2050, the global human population is predicted to increase by 2.5 billion reaching 9.6 billion people. To feed the world's 9.6 billion people, the Food and Agriculture Organization estimates that global food production must increase by 70%. Moreover, the productivity of major food crops is affected by environment induced abiotic stressors that further expand the food demand-supply gap. Among the food crops cereals are most important in ensuring food security, yet they are also the most vulnerable to abiotic stresses. Due to various abiotic stressors, cereal productivity is decreasing; thus, mitigating these yield losses is critical for all nations to satisfy rising food demands. Besides abiotic stressors, ongoing climate change are also posing severe obstacles to obtaining the required agricultural production levels to meet the expanding food demands. Among the abiotic stresses drought, temperature and soil salinity are the most severe, resulting in massive crop yield losses. Therefore, tolerance to abiotic stresses has typically been a long-term goal for plant breeders. In this

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chapter, the consequences of abiotic stresses, mechanism of abiotic stress tolerance and the role of various breeding strategies in developing abiotic stress-tolerant cultivars have been discussed.

**Keywords**

Cereals · Plant breeding · Abiotic stress · Mutation breeding · Quantitative trait loci

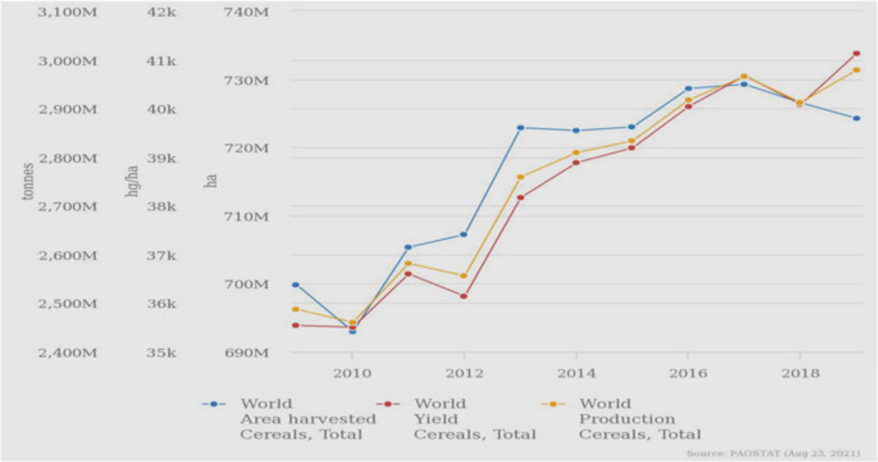
## 8.1 Cereals: An Ideal Crop to Achieve Food Security

Cereal is derived from the Latin word ‘cerealis’, which means ‘grain’, and refers to a type of fruit called a caryopsis, which is made up of endosperm, germ and bran. Cereals, such as wheat, rice, maize, sorghum, millet, barley and rye, are annual grass members of the grass family (a monocot family Poaceae, commonly known as Gramineae), with long, thin stalks and starchy grains used as food. Cereals have evolved to thrive in settings where they are frequently subjected to various stressors, including high temperatures, drought, salt, mineral toxicity and water scarcity (Giordano et al. 2021; Kumari et al. 2021). They are widely used crops in global agriculture, with approximately 2979 million tonnes being harvested worldwide in 2019 (FAOSTAT 2021 http://www.fao.org/faostat/en/). Maize, wheat and rice are the three most significant cereal crops, accounting for at least 85% of global grain output. In 2019, 1148.49, 765.77 and 755.47 million tonnes of rice, wheat and maize, respectively, were harvested (Table 8.1). The cereal statistics for the area harvested and grain yield in the last 10 years showed significant growth and thus

**Table 8.1** Worldwide total production of different cereals (2019)

| Cereals | Production value (million tonnes) |
|---|---|
| Maize | 1148.49 |
| Wheat | 765.77 |
| Rice, paddy | 755.47 |
| Barley | 158.98 |
| Sorghum | 57.89 |
| Millet | 28.37 |
| Oats | 23.10 |
| Triticale | 14.06 |
| Rye | 12.80 |
| Cereals nes | 7.91 |
| Grain, mixed | 3.42 |
| Buckwheat | 1.61 |
| Fonio | 0.70 |
| Canary seed | 0.24 |
| Quinoa | 0.16 |
| Cereals, total | 2978.98 |

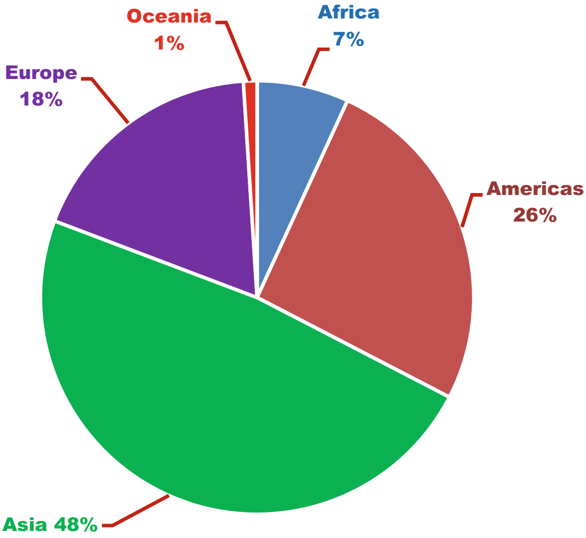
Source: FAOSTAT 2021, http://www.fao.org/faostat/en/



Source: FAOSTAT (Aug 23, 2021)

**Fig. 8.1** Comparative analysis on area harvested, yield and production of cereals globally (2009–2019)

**Fig. 8.2** Region-wise production share of cereals (2019)



positively impacted the production of cereals (Fig. 8.1). Cereals provide essential nutrients including proteins, carbohydrates, minerals, amino acids, fibres and micronutrients, including vitamins, magnesium and zinc (O'Neil et al. 2010; Papanikolaou and Fulgoni 2017).

Globally, 48% of the world’s cereal grains are produced in Asia, 26% in America and 18% in Europe (Fig. 8.2). Rice, sorghum, millet and wheat are commonly grown in Asia; corn and sorghum are grown in the United States, while barley, rye and oats are grown in Europe. Cereals are an essential source of nutrients in industrialized and

**Table 8.2** Comparative nutritive value of cereal grains

| Factor | Wheat | Maize | Rice | Barley | Sorghum |
|---|---|---|---|---|---|
| Available CHO (%) | 69.7 | 63.6 | 64.3 | 55.8 | 62.9 |
| Energy (kJ/100 g) | 1570 | 1660 | 1610 | 1630 | 1610 |
| Digestible energy (%) | 86.4 | 87.2 | 96.3 | 81.0 | 79.9 |
| *Vitamins (mg/100 g)* | | | | | |
| Thiamin | 0.45 | 0.32 | 0.29 | 0.10 | 0.33 |
| Riboflavin | 0.10 | 0.10 | 0.04 | 0.04 | 0.13 |
| Niacin | 3.7 | 1.9 | 4.0 | 2.7 | 3.4 |
| *Amino acids (g/16 g N)* | | | | | |
| Lysine | 2.3 | 2.5 | 3.8 | 3.2 | 2.7 |
| Threonine | 2.8 | 3.2 | 3.6 | 2.9 | 3.3 |
| Methionine and cysteine | 3.6 | 3.9 | 3.9 | 3.9 | 2.8 |
| Tryptophan | 1.0 | 0.6 | 1.1 | 1.7 | 1.0 |
| *Protein quality (%)* | | | | | |
| True digestibility | 96.0 | 95.0 | 99.7 | 88.0 | 84.8 |
| Biological value | 55.0 | 61.0 | 74.0 | 70.0 | 59.2 |
| Net protein utilization | 53.0 | 58.0 | 73.8 | 62.0 | 50.0 |
| Utilization protein | 5.6 | 5.7 | 5.4 | 6.8 | 4.2 |

Source: USDA National Nutrient Database for Standard Reference

developing countries, although their usage patterns differ. More than 70% of total grain output is used as feed for livestock in affluent nations, whereas 68 to 98% of cereal production is used for human consumption in developing countries (Olugbire et al. 2021).

Compared to dietary legumes and oilseeds, cereal grains have a low protein level, with rice having the lowest. In all cereal grains, lysine is the most limited of the necessary amino acids for humans. Cysteine, methionine and sulphur-containing amino acids are abundant in most grain proteins. Among the cereal crops, barley has a higher lysine content. The presence of antinutrients such as metal chelates, antivitamins, goitrogens, cyanogens, protease and amylase inhibitors, toxic phenolic glycosides and amino acid derivatives are known to influence the consumption of legumes (Mohan et al. 2016). As a result, adequate processing of the cereal-legume combination is necessary before ingestion to reduce these antinutrients. Cereal grain products have lower nutritional and sensory characteristics compared to animal meals. Physical, chemical, biological and physiological changes can improve the grain nutritional and visual characteristics (Piltz et al. 2021). Furthermore, natural processes such as fermentation and regulated germination with natural microflora help to improve the quality of cereal-based foods. The nutritional qualities of the most important cereal crops are furnished in Table 8.2.

## 8.2 Abiotic Stresses: Impact on Cereal Production

It is often difficult to breed a species for more than one robust feature at a time since individual plants react so differently to similar abiotic stress stimuli, but that is precisely what plant breeders are aiming for. Globally, abiotic and biotic stresses reduce average yield by more than 50% (Oerke et al. 1999; Raina and Khan 2020). However, abiotic stresses, especially salinity, drought, and temperature, are the major constraints for cereal production (Acquaah 2007; Martinez-Beltran and Manzur 2005; Munns 2002; Lobell and Field 2007). Abiotic stressors have a negative impact on several growth phases (Raina et al. 2020a). They are highly complicated, affecting crop dynamisms such as blooming, grain filling and maturity at the transcriptome, cellular and physiological levels (Atkinson and Urwin 2012; Maiti and Satya 2014; Paul and Roychoudhury 2019). The primary abiotic stressors impacting contemporary agricultural systems are atmosphere, soil, water and related variables (Sahu et al. 2014). Water is a major factor that induces abiotic stress in cereals, including water scarcity, salinity and waterlogging. Water scarcity, falling rainfall and rising temperature are the major limitations for agriculture, all of which substantially impact agricultural productivity.

### 8.2.1 Drought Stress

Undeniably, drought is one of the principal abiotic stresses in the world. Drought stress affects various morpho-physiological aspects of the plant from anthesis to maturity and significantly reduces productivity. The need of the hour is to develop stress-resistant genotypes which could thrive well under severe environment (Rabara et al. 2021). In most cases, rainwater produces a flooded condition in the field. Since water replaces almost all air in soil pore space, the oxygen content in flooded conditions decreases to zero within 24 h. Roots require oxygen to maintain vital cellular processes and cell viability. Waterlogging reduces the amount of oxygen available to the roots; if the roots consume any residual oxygen from flooded or waterlogged soils, the biological functions of the roots will get disrupted. As a result, the leaves and stems cannot acquire sufficient minerals and nutrients, and the roots begin to die due to waterlogging (Liliane and Charles 2020).

### 8.2.2 Temperature Stress

Crop species have been divided into three categories based on their temperature sensitivity: chilling-sensitive, freezing-sensitive and freezing-resistant plants (Kai and Iba 2014). Freezing may affect growth and produce frost-hardening/cold hardening, as well as causing the formation of reactive oxygen species, which could disrupt membrane components and induce protein denaturation (Beck et al. 2004; Baek and Skinner 2012). The crops subjected to a high temperature result in expansion-induced lysis, phase changes, lesions in membranes and physical damage (Tomás et al. 2020).

### 8.2.3 Salinity Stress

Salinity stress has various consequences in plants, including ionic and osmotic effects, nutritional and hormonal imbalances and the formation of reactive oxygen species (Rao et al. 2019). The buildup of sodium ($Na^+$) and chloride ($Cl^-$) ions has a significant impact on plant development and production, resulting in ionic, osmotic and oxidative stress (Yildiz et al. 2020). Multiple metabolic activities, such as protein translation, transcription and enzyme activity, are influenced by $Na^+$, resulting in osmotic stress. There is a genetic basis for salt responsiveness, as evidenced by salt-tolerant and salt-sensitive crop species (Roychoudhury et al. 2008). Salt tolerance across varieties has been recognized since the 1930s (Epstein 1977, 1983), and intra-specific salt tolerance selection has been documented in rice (Akbar and Yabuno 1977) and barley (Epstein et al. 1980).

### 8.2.4 Heavy Metal Stress

Abiotic stress arises from soil-related factors including soil properties, pollution and degradation. The injudicious use of certain hazardous pesticide chemicals facilitates their entry in the natural environment in various ways based on their solubility. Abiotic stress can also be caused by a nutrient shortage or the presence of harmful chemicals in the soil, such as heavy metals (Sahu et al. 2014). Heavy metals including manganese, zinc, copper, magnesium, molybdenum, boron and nickel substantially impact plant morphological, metabolic and physiological abnormalities (Roychoudhury et al. 2012). It includes shoot chlorosis, lipid peroxidation and protein breakdown (Emamverdian et al. 2015). Nutrient insufficiency has long been thought to be the root cause of low agricultural yields. Only 3.03 billion hectares (22%) of the world's 13.5 billion hectares is cultivable, while over two billion hectares is not suitable for cultivation. Oil shale disposal, soil heavy metal pollution and crude oil leakage negatively impact the root systems (Shah and Wu 2019).

In addition to the above-mentioned stresses, plant tissues are injured when the weather is hot, humid and foggy with a slight breeze. Plant reproductive development, chlorosis and necrosis are all affected by chilling stress, which includes decreased leaf growth and wilting. Ultraviolet and ionizing radiations have a variety of effects on the growth and development of cereal crops. Radiation affects stomatal function, cell survival, seed development and fertility (Foroughbakhch Pournavab et al. 2019; Metwally et al. 2019). Photon irradiation causes cellular damage in root and leaf tissues of cereals. Fast-flowing winds also reduce the phytohormonal content of cereal crop roots and shoots. The wind direction and velocity have an impact on plant growth and development (Sahu et al. 2014). Rainfall is one of the major abiotic stress variables impacting soil erosion and crop productivity in rain-fed agriculture in semi-arid areas. It regulates the acidity and salinity of the soil. Acid rain occurs when sulphur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) combine with water and oxygen in the atmosphere (Gong et al. 2019). Acid rain impairs vital processes of growth and development in cereal crops.

## 8.3 Origin of Abiotic Stress Tolerance

The origin of abiotic stress tolerance in agricultural plants can be found in a variety of places. Landraces, wild relatives, high-yielding varieties, initial breeding materials and advanced breeding materials may all harbour tolerance. Landraces from arid regions have been effectively employed in breeding to create open-pollinated types or hybrids for water-scarce situations. Abiotic stress providers include wild species and progenitors of our farmed crops (Table 8.3). The likelihood of identifying the desired genes and even the projected challenges and expected success in introgression of these genes into the chosen recurrent cultivar all influence the genetic resource used as a source for abiotic stress resistance. A substantial genetic diversity occurs in the breeding materials and even in some improved cultivars of different crop species for drought and salinity resistance (Basu and Roychoudhury 2021). Because this is the least troublesome of all sources of drought and salinity resistance, an initial aim of the breeder should be to find and use such sources. Drought and salt resistance traits are often found in landraces (old or desi varieties) that have evolved and are adapted to drought and salinity conditions. Efforts in utilizing wild relatives should be concentrated only when the diversity in top breeding materials and landraces has been exhausted.

**Table 8.3** Wild sources of resistance to drought and salinity in some cereal crop plants

| Crop | Wild species | Resistance |
|---|---|---|
| Wheat (*Triticum aestivum* L.) | *Aegilops kotschyi* | Drought tolerance |
| | *Agropyron seirpea* | Salinity tolerance |
| | *Triticum urartu* | Drought tolerance |
| Rice (*Oryza sativa* L.) | *Porteresia coarctata (O. coarctata)* | Salinity tolerance |
| | *O. rufipogon* | Cold tolerance |
| | *O. glaberrima* | Drought and heat tolerance |
| | *O. barthii* | Drought and heat tolerance |
| | *O. meridionalis* | Drought and heat tolerance |
| | *O. rufipogon* | Acid soil and aluminium tolerance |
| Maize (*Zea mays*) | *Eastern gamagrass* | Drought; acid soil and aluminium; salinity tolerance |
| | *Z. nicaraguensis* | Waterlogging tolerance |
| | *Z. luxurians* | Waterlogging tolerance |

## 8.4 Response of Cereals Towards Abiotic Stress

Cereals have a diverse set of strategies at the genetic, physiological, biochemical and molecular levels. Nevertheless, new progress in traditional, marker-assisted breeding and genetic engineering has made it possible to develop drought-tolerant crops (Oladosu et al. 2019; Rosero et al. 2020). Many crops are sensitive to high salinity and could not withstand saline conditions; however, certain crops are adapted to thrive in harsher salt environment prevalent in coastal locations like salt marshes. The high rate of evaporation within those areas concentrates salts in the mineral composition of the soil. These crops have evolved morpho-physiological and reproductive adaptations to salty, waterlogged and anaerobic environments. Such crops can withstand salt stress primarily through three main mechanisms: osmotic tolerance, ion exclusion and tissue tolerance. Long-distance signalling waves control osmotic tolerance by reducing cell growth in root tips, leaves and regulate stomatal conductance (Rajendran et al. 2009; Roy et al. 2014). Ion exclusion is primarily concerned with the transfer of sodium ($Na^+$) and chlorine ($Cl^-$) into roots, which prevents the buildup of $Na^+$ in shoots. Tissue tolerance entails exposing tissues to accumulating $Na^+$ and $Cl^-$ at the cellular and subcellular levels, the build up of suitable solutes and the enzyme that catalyzes the detoxification of reactive oxygen species (Reddy et al. 2017). The capacity of cereal crops to withstand dominating abiotic stress, which includes water deficiency (drought), flood (anoxia), salinity, high/low temperature and other osmotic stressors, is an essential component of yield resilience and has long been a goal for plant breeders (Halford et al. 2014). Due to the ever-increasing population, the fast-changing global environment impacts agricultural production and food supply, resulting in a need for stress-tolerant crop (Takeda and Matsuoka 2008; Newton et al. 2011). Understanding how plant responses to diverse stressors, interact at the molecular level is critical for creating stress-tolerant crops (Paul and Roychoudhury 2019). The adaptive mechanism of abiotic stress in plants is associated with various traits are shown in Fig. 8.3.

## 8.5 Different Breeding Strategies for Improving Abiotic Stress Tolerance

Genetic modification for effective stress tolerance in plants is difficult due to the complex characteristics of abiotic stress events (Wang et al. 2007). Breeding for abiotic stress is an important strategy to fight yield loss. Even in ancient times, the necessity for stress-tolerant crops was obvious (Jacobsen and Adams 1958). However, efforts to increase crop performance under environmental stressors have mostly failed due to a lack of understanding of the underlying processes of stress tolerance in plants. Information on the genetic basis of abiotic stress tolerance, method of inheritance, size of gene effects, heterosis, combining ability and their mechanism of action are required to plan effective breeding programmes for generating abiotic stress-tolerant cultivars. Breeding methodology for crops should be adopted based on the type of reproduction, i.e. whether the species is self- or cross-pollinating.

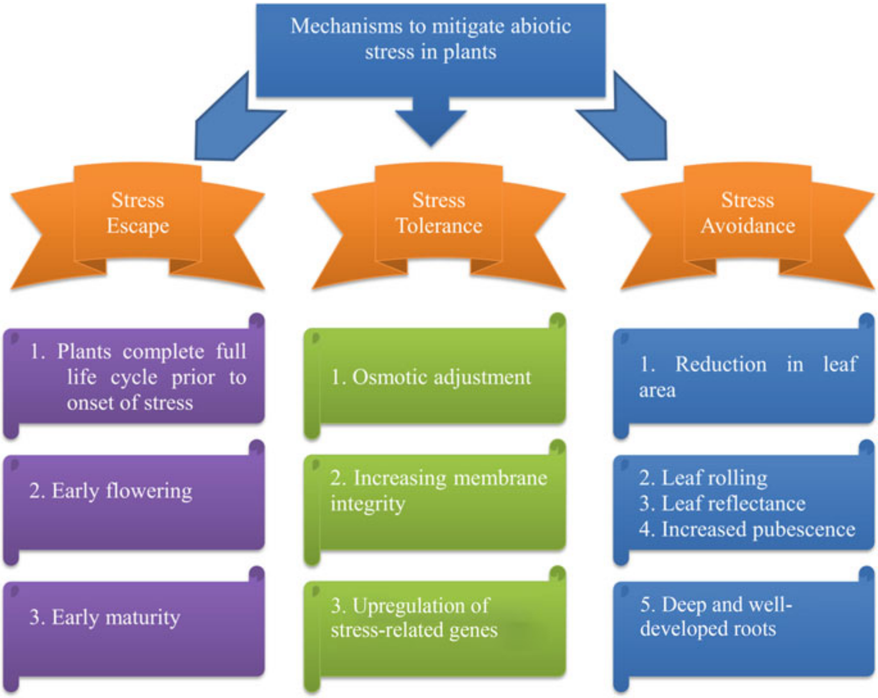


**Fig. 8.3** Abiotic stress adaptive mechanism and their associated traits

Pedigree and bulk methods may be employed for self-pollinated crops, whereas recurrent selection could be used for cross-pollinated crops. However, if the goal is to transfer a few stress-resistant characteristics to a high-yielding genotype, backcrossing is an appropriate strategy. Pedigree, modified bulk pedigree and anther culture approaches were used to create salinity-tolerant varieties. On the other hand, biparental mating (half-sib and full-sib) preserves a wide genetic basis while also allowing for the evolution of drought-resistant genotype (Yunus and Paroda 1982).

Nowadays, breeding strategies for improving abiotic stress tolerance include both conventional and non-conventional approaches. Various factors influence selecting an appropriate breeding programme developing stress-tolerant cultivars, including screening methodologies, sources and mechanisms of tolerance, gene action and heredity and their link to agronomic characteristics.

### 8.5.1 Conventional Approaches

Conventional approaches in plant breeding include selection and introduction, pedigree method, modified bulk pedigree method, shuttle breeding, mutation breeding, diallel selective mating system supplemented by marker-assisted selection (MAS), backcross method and recurrent selection. The timing, duration and severity of the stress are three key aspects for successful stress-resistance breeding. Using traditional breeding procedures, abiotic stress-tolerant lines of crops such as rice, wheat, maize and barley have been developed. However, identifying traits that correlate well with drought tolerance is difficult using this technique. Traditional efforts to develop crop plants resistant to abiotic stress have had mixed results (Richards 1996). This is attributed to various variables, including complexity caused by genotype due to environment (G × E) interactions. Stress-tolerant crop cultivars can be created through various methods, including introduction, selection, hybridization and mutation breeding. However, mutation breeding is considered a coherent and widely accepted tool to enhance abiotic stress tolerance in cereals.

#### 8.5.1.1 Mutation Breeding

Nonetheless, conventional breeding approaches are laborious and time-consuming and do not yield the desired variation (Cassells and Doyel 2003). Therefore, agronomists are putting efforts into searching alternate ways to get the desired variation in crops within a short time. In this regard, mutation breeding is a coherent tool to generate mutants with desirable traits and enhanced genetic variability. Mutations are sudden heritable changes in an organism genome that play an essential role in increasing genetic variability (Hugo de Vries 1901). Mutations occur both spontaneously and are induced using different physical, chemical and combined mutagens. However, the frequency of spontaneous mutations is low and is not enough to meet the needs of crop improvement programmes. Therefore, mutations are induced artificially to enhance the frequency of mutations. In the beginning, Muller (1927), employed X-rays to irradiate *Drosophila* flies to enhance genetic variability. The discovery of the mutagenic potential of X-rays in maize and barley was the pioneering event in the establishment of mutation breeding for crop improvement programmes (Stadler 1928). The induction of mutations within an organism genome has been used in plant breeding since the discovery of the mutagenic effects of X-rays on *Drosophila* flies (Muller 1927). These discoveries on the induction of artificial mutations encouraged plant breeders to use different physical and chemical mutagens for crop improvement programmes. As a result, thousands of mutant varieties with improved yield, quality, stress tolerance and adaptability were developed in various crop species. Mutation breeding is now an established breeding strategy to achieve crop varieties with improved agronomic traits, including abiotic stress tolerance in cereals.

#### 8.5.1.2 Role of Mutation Breeding in Improving Abiotic Stress Tolerance in Cereals

Nowadays, mutation breeding for crop improvement is based on physical and chemical mutagens and variations in in vitro culture, called ‘somaclonal variation’. The use of induced mutation for crop improvement is reflected by the fact that 3364, including 1596 improved mutant varieties of cereals, have been developed and officially released (Raina et al. 2016). These mutant varieties are cultivated on millions of hectares of cultivated land that generate billions of dollars (Laskar et al. 2018a, b; Goyal et al. 2019a, b). This has led to a tremendous economic impact on agriculture and its allied sectors worldwide (Das et al. 2014; Khursheed et al. 2018a, b, c). Ever since the historical discoveries of Muller and Stadler, different mutagens were employed to enhance genetic variability. However, radiations were preferred to achieve the improved genetic variability in food crops (Hassan et al. 2018; Laskar et al. 2019). In the last five decades, various countries such as China, India, Pakistan, Bangladesh, Vietnam, Thailand, Italy, Sweden, the United States of America, Canada and Japan took up extensive crop improvement programmes through induced mutagenesis. This has made remarkable achievements in developing elite mutant varieties in a wide range of food crops, particularly cereals and pulses (Raina et al. 2019; Wani et al. 2021a, b).

Mutation breeding has been successful in developing mutant varieties with improved tolerance to abiotic stresses (Laskar et al. 2015; Khursheed et al. 2019; Goyal et al. 2021). The improved mutant varieties play a vital role in mitigating the chronic hunger and malnutrition issues and achieving global food and nutrition security (Khursheed et al. 2016; Goyal et al. 2020a, b). Mutation breeding offers an opportunity to improve abiotic stress tolerance without altering the genetic constitution (Raina et al. 2017; Tantray et al. 2017). Unlike genetically engineered crops, mutant varieties do not possess any alien genes. Hence, there are no detrimental issues of induced mutations associated with human health, religious and social ethics. In the last two decades, enormous advances have been achieved in this field, and thousands of mutants have been released as new cultivars (Wani et al. 2017; Ansari et al. 2021). In rice, the results have been remarkable. The FAO/IAEA database displays about 853 mutant varieties of rice, 311 mutant varieties of barley, 298 varieties of wheat and 96 mutant varieties of maize developed by the use of induced mutations (https://mvd.iaea.org/ accessed on 10-07-2021). Till now, 160 mutant varieties of cereals have been developed that reflect improved tolerance to a wide range of abiotic stresses such as drought, heat, salinity and cold (Baloch et al. 2002; Saleem et al. 2005; Cassells and Doyel 2003; Parry et al. 2009) (Table 8.4). For instance, rice seeds irradiated with carbon or neon ions have generated a high salt tolerance mutant variety (Hayashi et al. 2007). The gamma radiation mutant rice varieties, Zhefu 802 and Basmati 370, revealed improved cold tolerance (Ahloowalia et al. 2003). Likewise Bastion, Secret and Taran are cold-tolerant barley mutant varieties (Shevtsov et al. 2003). In Finland, a barley mutant, Balder J, had a higher yield and improved drought resistance (Kharkwal and Shu 2009). Luther and Pennrad are high-yielding and lodging-resistant barley mutant varieties (Kharkwal and Shu 2009).

Many such varieties of abiotic stress-tolerant mutant crops have been released in different countries all over the world (Raina and Danish 2018; Raina et al. 2020b). Therefore, induced mutagenesis for resistance to abiotic stresses is a possible breeding approach that creates new desirable genetic variability of agronomic importance (Amin et al. 2016, 2019; Raina et al. 2018a, b). Thus, mutation-assisted plant breeding has a crucial role in developing 'designer crop varieties' to address the qualms and challenges of global climate variability and plant-product insecurity (Raina et al. 2021a, b, c). Both efficiency and efficacy of mutation techniques in crop breeding can significantly be increased through molecular mutation breeding. High-

**Table 8.4** Mutant varieties of cereals with improved tolerance to abiotic stresses (Source: MVD 2021)

| Country | Year | Latin name | Mode of development, mutagen and dose used | Improved tolerance to |
|---|---|---|---|---|
| Finland | 1975 | *Secale cereale* L. | Gamma rays (100 Gy) | Low temperature stress |
| Russian Federation | 1993 | *Panicum miliaceum* L. | It was developed by hybridization with two chemo mutants | Drought stress |
| United States | 1991 | *Avena sativa* L. | It was developed by hybridization with mutant Florida 501 | Low temperature stress |
| Russian Federation | 1984 | *Sorghum sudanense (Piper) Stapf* | Dimethyl sulphate | Drought and lodging stress |
| China | 1974 | *Oryza sativa* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1979 | *Oryza sativa* L. | Gamma rays (350 Gy) | Low temperature and lodging stress |
| China | 1977 | *Oryza sativa* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1981 | *Oryza sativa* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1981 | *Oryza sativa* L. | Gamma rays | Low temperature stress |
| China | 1976 | *Oryza sativa* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1968 | *Oryza sativa* L. | Gamma rays (300 Gy) | Salinity stress |
| China | 1981 | *Oryza sativa* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1975 | *Oryza sativa* L. | Fast neutrons | Low temperature stress |
| China | 1980 | *Oryza sativa* L. | Gamma rays (350 Gy) | Low temperature stress |
| China | 1980 | *Oryza sativa* L. | Gamma rays (200 Gy) | Heat stress |
| China | 1973 | *Oryza sativa* L. | Gamma rays (200 Gy) | Drought stress |

(continued)

**Table 8.4** (continued)

| Country | Year | Latin name | Mode of development, mutagen and dose used | Improved tolerance to |
|---|---|---|---|---|
| China | 1977 | *Oryza sativa* L. | Gamma rays (350 Gy) | Low temperature stress |
| China | 1986 | *Oryza sativa* L. | Gamma rays (186.9 Gy) | Low temperature stress |
| India | 1980 | *Oryza sativa* L. | X-rays (300 Gy) | Drought stress |
| India | 1984 | *Oryza sativa* L. | EMS (0.2%) | Lodging stress |
| India | 1976 | *Oryza sativa* L. | Gamma rays (220 Gy) | Salinity stress |
| India | 1983 | *Oryza sativa* L. | Gamma rays | Salinity stress |
| India | 1988 | *Oryza sativa* L. | It was developed by hybridization with mutant Jaya induced by gamma rays | Low temperature stress |
| Indonesia | 1983 | *Oryza sativa* L. | Gamma rays (200 Gy) | Salinity stress |
| Indonesia | 1988 | *Oryza sativa* L. | Gamma rays (400 Gy) | Drought and low pH stress |
| Japan | 1976 | *Oryza sativa* L. | It was developed by hybridization with one mutant variety Reimei obtained by irradiation of seeds with gamma rays (200 Gy) | Low temperature stress |
| Japan | 1966 | *Oryza sativa* L. | Gamma rays (200 Gy) | Low temperature and lodging stress |
| Japan | 1985 | *Oryza sativa* L. | It was developed by hybridization with mutant variety Mine-asahi obtained by irradiation of seeds with gamma rays (200 Gy) | Low temperature stress |
| Japan | 1988 | *Oryza sativa* L. | It was developed by hybridization with mutant variety Mutsukaori obtained by irradiation of seeds with gamma rays (200 Gy) | Low temperature stress |
| Japan | 1989 | *Oryza sativa* L. | It was developed by hybridization with mutant variety Reimei obtained by irradiation of seeds with 200 Gy gamma rays | Low temperature and lodging stress |
| Pakistan | 1987 | *Oryza sativa* L. | EMS (0.5%) | Salinity stress |
| Pakistan | 1993 | *Oryza sativa* L. | Gamma rays | Salinity stress |
| Vietnam | 1990 | *Oryza sativa* L. | It was developed by hybridization with two mutants induced by treatment of seeds with 0.015% N-methyl-N′-nitrosourea | Salinity stress |

(continued)

**Table 8.4** (continued)

| Country | Year | Latin name | Mode of development, mutagen and dose used | Improved tolerance to |
|---|---|---|---|---|
| China | 1992 | *Oryza sativa* L. | Gamma rays | Salinity stress |
| China | 1994 | *Oryza sativa* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1992 | *Oryza sativa* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1988 | *Oryza sativa* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1990 | *Oryza sativa* L. | Gamma rays | Salinity and alkalinity stress |
| China | 1993 | *Oryza sativa* L. | It was developed by hybridization with mutant variety Zhefu 802 obtained by irradiation with gamma rays (300 Gy) | Low temperature stress |
| China | 1998 | *Oryza sativa* L. | Gamma rays | Low temperature stress |
| Pakistan | 1999 | *Oryza sativa* L. | Fast neutrons (15 Gy) | Salinity stress |
| Thailand | 1978 | *Oryza sativa* L. | Gamma rays (150 Gy) | Drought stress |
| Vietnam | 1999 | *Oryza sativa* L. | NA | Salinity stress |
| Philippines | 1976 | *Oryza sativa* L. | Gamma rays (200 Gy) | Drought stress |
| China | 1981 | *Oryza sativa* L. | It was developed by hybridization with mutant Funong 709 | Low temperature stress |
| Vietnam | 1999 | *Oryza sativa* L. | Gamma rays (200 Gy) | Acid sulphate soil |
| Vietnam | 1999 | *Oryza sativa* L. | Gamma rays (200 Gy) | Acid sulphate soil and salinity stress |
| India | 1992 | *Oryza sativa* L. | NA | Salinity stress |
| India | 1993 | *Oryza sativa* L. | It was developed by hybridization with mutant variety Jagannath (BSS-873) obtained by irradiation of seeds with X-rays (300 Gy) | Low temperature stress |
| Cuba | 2007 | *Oryza sativa* L. | Protons (20 Gy) | Salinity stress |
| Cuba | 1995 | *Oryza sativa* L. | Fast neutrons (20 Gy) | Low temperature stress |

(continued)

**Table 8.4** (continued)

| Country | Year | Latin name | Mode of development, mutagen and dose used | Improved tolerance to |
|---|---|---|---|---|
| Cuba | NA | *Oryza sativa* L. | NA | Drought and salinity stress |
| Cuba | NA | *Oryza sativa* L. | NA | Drought and salinity stress |
| Cuba | NA | *Oryza sativa* L. | NA | Drought stress |
| Cuba | 1995 | *Oryza sativa* L. | Fast neutrons (20 Gy) | Drought stress |
| Malaysia | 2015 | *Oryza sativa* L. | Gamma rays (300 Gy) | Drought stress |
| Malaysia | 2015 | *Oryza sativa* L. | Gamma rays (300 Gy) | Drought stress |
| Thailand | 2017 | *Oryza sativa* L. | Gamma ray (20 Kr) | Photoperiod insensitive |
| Japan | 1986 | *Oryza sativa* L. | It was developed by hybridization with mutant variety Nadahikari obtained by irradiation with gamma rays | Low temperature stress |
| Japan | 1999 | *Oryza sativa* L. | It was developed by hybridization with mutant line derived from mutant variety Reimei induced by irradiation of seeds with gamma rays (200 Gy) | Low temperature stress |
| Japan | 2000 | *Oryza sativa* L. | It was developed by hybridization with mutant line derived from mutant variety Reimei and mutant variety Yama-uta induced by irradiation of seeds with gamma rays (200 Gy) | Low temperature stress |
| Japan | 2002 | *Oryza sativa* L. | It was developed by hybridization with mutant of mutant variety mine-Asahi obtained by irradiation of seeds with gamma rays (200 Gy) | Low temperature stress |
| Japan | 2004 | *Oryza sativa* L. | It was developed by hybridization with mutant variety Dewasansan obtained by irradiation of seeds with gamma rays (300 Gy) | Low temperature stress |
| Korea | 2007 | *Oryza sativa* L. | Gamma rays (50 Gy) | Salinity stress |
| China | 1968 | *Triticum aestivum* L. | Gamma rays (200 Gy) | Drought stress |
| China | 1968 | *Triticum aestivum* L. | Gamma rays (300 Gy) | Low temperature and lodging stress |
| China | 1968 | *Triticum aestivum* L. | Gamma rays (300 Gy) | Low temperature and lodging stress |

(continued)

**Table 8.4** (continued)

| Country | Year | Latin name | Mode of development, mutagen and dose used | Improved tolerance to |
|---|---|---|---|---|
| China | 1971 | *Triticum aestivum* L. | Gamma rays (200 Gy) | Low temperature stress |
| China | 1979 | *Triticum aestivum* L. | Gamma rays (350 Gy) | Lodging, drought and salinity stress |
| China | 1979 | *Triticum aestivum* L. | Gamma rays (300 Gy) | Drought stress |
| China | 1966 | *Triticum aestivum* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1983 | *Triticum aestivum* L. | Gamma rays (350 Gy) | Low temperature, salinity and drought stress |
| China | 1982 | *Triticum aestivum* L. | Beta rays | Drought stress |
| China | 1980 | *Triticum aestivum* L. | Gamma rays | Salinity, alkalinity and heat stress |
| China | 1974 | *Triticum aestivum* L. | Gamma rays | Salinity, alkalinity and low temperature stress |
| China | 1974 | *Triticum aestivum* L. | Gamma rays | Salinity, alkalinity and low temperature stress |
| China | 1971 | *Triticum aestivum* L. | It was developed by hybridization with mutant Yuannong 1 irradiated with gamma rays | Drought stress |
| China | 1968 | *Triticum aestivum* L. | Gamma rays (100 Gy) | Drought stress |
| China | 1968 | *Triticum aestivum* L. | Gamma rays (200 Gy) | Drought stress |
| China | 1973 | *Triticum aestivum* L. | Gamma rays | Drought stress |
| China | 1982 | *Triticum aestivum* L. | Gamma rays | Drought stress |
| China | 1969 | *Triticum aestivum* L. | Gamma rays (200 Gy) | Low temperature stress |
| China | 1975 | *Triticum aestivum* L. | Gamma rays (300 Gy) | Low temperature stress |
| China | 1986 | *Triticum aestivum* L. | Gamma rays (300 Gy) | Salinity and alkalinity |

(continued)

**Table 8.4** (continued)

| Country | Year | Latin name | Mode of development, mutagen and dose used | Improved tolerance to |
|---|---|---|---|---|
| China | 1984 | *Triticum aestivum* L. | Gamma rays (80 Gy) | Drought and lodging stress |
| China | 1982 | *Triticum aestivum* L. | It was developed by hybridization with one mutant M 70A2 | Drought stress |
| China | 1980 | *Triticum aestivum* L. | It was developed by hybridization with mutant 72 gamma-16 obtained by irradiation with gamma rays (200 Gy) | Drought stress |
| China | 1988 | *Triticum aestivum* L. | Gamma rays | Low temperature stress |
| China | 2004 | *Triticum aestivum* L. | Gamma rays (1.5 Gy) | Salinity and drought stress |
| China | 2004 | *Triticum aestivum* L. | Gamma rays (1.5 Gy) | Salinity and drought stress |
| Pakistan | 1996 | *Triticum aestivum* L. | Gamma rays (1400 Gy) | Drought stress |
| Russian Federation | 1984 | *Triticum aestivum* L. | Gamma rays (200 Gy) | Heat stress |
| Russian Federation | 1982 | *Triticum aestivum* L. | Gamma rays | Low temperature and lodging stress |
| Russian Federation | 1985 | *Triticum aestivum* L. | It was developed by hybridization with mutant KK1 induced with treatment of seeds with N-nitroso-N-ethyl urea | Low temperature and lodging stress |
| Russian Federation | 1989 | *Triticum aestivum* L. | It was developed by treatment of seeds with water solution of 0.01% ethyl imine | Low temperature and drought stress |
| Russian Federation | 1989 | *Triticum aestivum* L. | Water solution of NMU (0.01%) | Low temperature stress |
| Russian Federation | 1991 | *Triticum aestivum* L. | It was developed by hybridization with mutant variety Nemchinovskaya 86 induced by treatment of seeds with N-nitroso-N-ethyl urea | Low temperature and lodging stress |
| Russian Federation | 1992 | *Triticum aestivum* L. | Water solution of N-nitroso-N-methylurea (0.01%) | Low temperature stress |
| Russian Federation | 1992 | *Triticum aestivum* L. | It was developed by treatment of seeds with water solution of 0.01% ethylene imine | Low temperature and lodging stress |
| Bulgaria | 2009 | *Triticum aestivum* L. | Gamma rays (50 Gy) | Low temperature and drought stress |
| China | 2007 | *Triticum aestivum* L. | NA | Drought stress |

(continued)

**Table 8.4** (continued)

| Country | Year | Latin name | Mode of development, mutagen and dose used | Improved tolerance to |
|---|---|---|---|---|
| China | 2010 | *Triticum aestivum* L. | NA | Drought stress |
| Kenya | 2001 | *Triticum aestivum* L. | Gamma rays | Drought stress |
| China | 2011 | *Triticum aestivum* L. | Space mutagenesis and doubled haploid technique | Drought stress |
| Ukraine | 2017 | *Triticum aestivum* L. | Gamma rays (100, 150, 200, 250 Gy) | Drought stress |
| Ukraine | 2017 | *Triticum aestivum* L. | Nitrosomethylurea (0.0125% and 0.025%) | Drought stress |
| Ukraine | 2017 | *Triticum aestivum* L. | Nitrosomethylurea (0.0125% and 0.025%) | Drought stress |
| Ukraine | 2017 | *Triticum aestivum* L. | Gamma rays (100, 150, 200, 250 Gy) | Drought stress |
| Bulgaria | 2002 | *Triticum turgidum* ssp. *durum Desf.* | Gamma rays (50 Gy) | Low temperature and lodging stress |
| Bulgaria | 1988 | *Triticum turgidum* ssp. *durum Desf.* | Gamma rays (20 Gy) | Lodging and low temperature stress |
| Estonia | 1993 | *Hordeum vulgare* L. | It was developed by hybridization with mutant variety Liisa obtained by irradiation with X-rays (100 Gy) | Drought and lodging stress |
| Finland | 1960 | *Hordeum vulgare* L. | X-rays (60 Gy) | Drought stress |
| Greece | 1969 | *Hordeum vulgare* L. | Gamma rays | Low temperature stress |
| Iraq | 1994 | *Hordeum vulgare* L. | Gamma rays (200 Gy) | Lodging stress |
| Turkey | 1998 | *Hordeum vulgare* L. | Gamma rays (150 Gy) | Low temperature and drought stress |
| Turkey | 1998 | *Hordeum vulgare* L. | Gamma rays (150 Gy) | Low temperature and drought stress |
| United States | 1963 | *Hordeum vulgare* L. | Thermal neutrons | Low temperature stress |
| Russian Federation | 1982 | *Hordeum vulgare* L. | N-Nitroso-N-ethyl urea | Low temperature and lodging stress |
| Russian Federation | 1988 | *Hordeum vulgare* L. | Ethylene oxide (0.02%) | Lodging and drought stress |

(continued)

**Table 8.4** (continued)

| Country | Year | Latin name | Mode of development, mutagen and dose used | Improved tolerance to |
|---|---|---|---|---|
| Russian Federation | 1988 | *Hordeum vulgare* L. | It was developed by hybridization with mutant 52 M1 resistant to winter (induced by NDMU) and with mutant variety Novator ((Zavet × start) × 31 M15) induced by N-nitroso-N-ethyl urea (NEU) | Low temperature and lodging stress |
| Russian Federation | 1995 | *Hordeum vulgare* L. | N-Nitroso-N-ethyl urea (0.025%) | Low temperature and lodging stress |
| Czech Republic | 1978 | *Hordeum vulgare* L. | It was developed by hybridization with [(/Valticky × Kneifel/ × Diamant) × Arabische G] | Drought stress |
| Russian Federation | 1990 | *Hordeum vulgare* L. | N-Nitroso-N-ethyl urea (0.06%) | Low temperature and lodging stress |
| Germany | 1955 | *Hordeum vulgare* L. | X-rays (100 Gy) | Low temperature and lodging stress |
| Syrian Arab Republic | 2000 | *Hordeum vulgare* L. | Gamma rays (100 Gy) | Lodging and drought stress |
| Bulgaria | 1983 | *Hordeum vulgare* L. | Gamma rays (100 Gy) | Low temperature stress |
| Ukraine | 2000 | *Hordeum vulgare* L. | It was developed by hybridization with mutant Kharkivskiy 99 | Drought stress |
| Russian Federation | 2001 | *Hordeum vulgare* L. | N-Nitroso-N-ethyl urea (0.1%) | Low temperature stress |
| Bulgaria | 1982 | *Hordeum vulgare* L. | It was developed by hybridization with mutant variety Markeli 5 obtained by irradiation gamma rays (400 Gy) | Low temperature stress |
| Jordan | NA | *Hordeum vulgare* L. | NA | Drought stress |
| Bulgaria | 1994 | *Zea mays* L. | It was developed by hybridization with mutant (from the cross XM-88-113 (female) × Mol17 (male)). The mutant parent was derived from the treatment of seed of B-84 with 0.001% N-nitroso-N-ethyl urea followed by 1% dioxane | Drought stress |
| Bulgaria | 1993 | *Zea mays* L. | It was developed by hybridization with mutant (from the cross mutant XM-87-136 (female) and maize cultivar Mol17 (male)). The mutant was derived from the treatment of | Drought stress |

(continued)

**Table 8.4** (continued)

| Country | Year | Latin name | Mode of development, mutagen and dose used | Improved tolerance to |
|---|---|---|---|---|
| | | | seed of B-37 with 0.2% dimethyl sulphate followed by 0.05% dimethyl amino azobenzene followed by 1% dioxane | |
| Bulgaria | 1992 | *Zea mays* L. | It was developed by hybridization with mutant (from the cross B-579 × B-84 selection (female parent) and the mutant XM-552 (male) | Drought stress |
| China | 1992 | *Setaria* sp. | Gamma rays (250 Gy) | Drought stress |
| China | 1999 | *Setaria* sp. | Gamma rays (250 Gy) | Drought stress |
| China | 1995 | *Setaria* sp. | It was developed by crossing with one mutant | Drought and lodging stress |
| China | 1987 | *Setaria* sp. | Fast neutrons | Drought stress |
| China | 1989 | *Setaria* sp. | Fast neutrons | Drought stress |
| China | 1985 | *Setaria* sp. | NA | Drought and low temperature stress |
| China | 1985 | *Setaria* sp. | NA | Drought and low temperature |

throughput DNA technologies such as targeting induced limited lesions in genomes, high-resolution melt analysis and Ecotype targeting induced local lesions in genomes are the key techniques and resources in molecular mutation breeding (Das et al. 2014). Unlike biotic stresses, herbicides, pesticides and fertilizers cannot mitigate the harmful effects of abiotic stresses.

### 8.5.2 Non-Conventional Approaches

The traditional breeding method has been sluggish in creating high-yielding, stress-tolerant cultivars, owing to challenges in accurately defining the target environment, complicated interactions of stress tolerance with surroundings and a lack of adequate screening methods (Cooper et al. 1999; Wade et al. 1999). The necessity for numerous backcrosses to remove undesired characteristics, restriction to loci that provide a readily apparent phenotype and inadequacy if the gene pool lacks sufficient diversity in the trait of interest are all key drawbacks of traditional breeding. As a result, the current focus is on marker-aided breeding, which allows for the ‘pyramiding’ of desired characteristics for faster crop development with minimal resource input. Non-conventional approaches and discoveries such as the somaclonal approach, F1 anther culture, marker assisted selection and genetically modified crops are the most recent advances in developing abiotic stress tolerance in cereals. The most immediate and future solutions for increasing abiotic stress tolerance in cereal crops might be the recent ground breaking developments in bioinformatics and integrating omics technology. Identifying the genetic basis of stress tolerance and using the required salt stress tolerance-associated genes or QTL (quantitative trait loci) to produce varieties with increased salinity tolerance are prerequisites for improving salt tolerance. Omics techniques, such as genomics, functional genomics, genetic engineering, gene expression, protein or metabolite profile(s) and their overall phenotypic impacts, contribute to a better knowledge of stress tolerance mechanisms at the molecular level. The discovery and characterization of genes and particular genomic areas linked with quantitative and qualitative agronomic characteristics that have been critical in crop breeding approaches. A high-throughput marker-assisted approach has been widely employed in recent breeding projects to improve selection effectiveness and precision. The exploitation of natural genetic variants, either through direct selection in stressful situations or by the identification of QTLs and subsequent marker-assisted selection, and creating transgenic plants to introduce new genes or change the expression levels of existing genes to influence salt stress resistance are two primary techniques now being used to increase stress resistance. Simple genetic models were used to assess the genetic basis of stress tolerance in plants in the beginning. With the advent of molecular markers, inheritance of salt tolerance became more manageable since particular QTLs could be discovered. It is now feasible to establish the genetic basis of a trait and map particular chromosomal segments or QTL and estimate the relative contribution of each QTL to the variation of a trait. Genomic maps have been created in several crops to exploit genetic diversity, tag qualitative and quantitative characteristics (Butruille et al. 1999) and assess the stability of identified QTL across diverse environmental conditions (Hittalmani et al. 2002). Stable and consistent QTLs offer a great way to increase selection efficiency, especially for characteristics that are regulated by several genes and heavily impacted by the environment, such as salinity (Dudley 1993). The effectiveness of marker assisted selection is influenced by several parameters, including the distance between observed QTL and marker loci (Dudley 1993) and the fraction of total additive variation explained by the QTL (Lande and Thompson 1990). New genomic technologies are promising to advance breeding resistance to these stressors due to a better understanding of underlying mechanisms and identifying the implicated genes. Modern biotechnological tools such as genetic engineering have successfully developed transgenic plants resistant to various abiotic stresses (Jewell et al. 2010). However, stress-resistant transgenic plants did not receive public acceptance due to risks concerning human health, social and religious issues and environmental safety (Carpenter 2010; James 2011; Kathage and Qaim 2012; Seralini et al. 2012). Hence, conventional breeding methods seem more appropriate to develop stress-tolerant and environment-friendly crop varieties.

## 8.6 Conclusions and Future Directions

The majority of crop losses are caused by abiotic stressors, which account for more than half of all harvest losses. According to several research findings, salt and drought stress have a detrimental effect on plant growth, development, physiology and production. During the last century, conventional plant breeding significantly enhanced crop quality and yield and improved abiotic stress resistance, such as drought and salinity tolerance. However, establishing abiotic stress tolerance varieties/hybrids will take longer time. Crop varieties/lines/hybrids with higher tolerance to drought, salinity, high temperature and nutrient deficiency, developed through conventional and molecular breeding methods and genetic engineering, are important for meeting global food demands. Traditional breeding knowledge combined with marker-assisted selection makes it quicker and more effective to generate drought tolerance in crop plants using genotypic data to improve and sustain productivity in drought-prone environmental settings. There is a pressing need to develop strategies to boost food output, particularly in the stressed zones of the world. A breeder must identify the genetic basis of stress tolerance in crop plants to generate improved genotypes using either traditional breeding or biotechnological methods. Scientists from all around the globe are working hard to develop varieties with enhanced heterosis in stress-prone settings. The most promising, less resource-intensive, commercially feasible and socially acceptable strategy is to develop crop varieties with built-in salt, drought and heat tolerance.

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